REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE** Technical Papers	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		**8. PERFORMING ORGANIZATION REPORT**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S NUMBER(S)**

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20021031 078

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	A		Leilani Richardson **19b. TELEPHONE NUMBER** *(include area code)* (661) 275-5015

8 separate items enclosed

S7 TP-FY99-0050

MEMORANDUM FOR PRR (In-House Publication)

✓ Spreadsheet
✓ DTS

FROM: PROI (TI) (STINFO)

11 May 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-FY99-0050
Spanjers, Schilling, Engleman, and Spores "The Micro Pulsed Plasma Thruster"

Journal Article **(Public Release)**

The Micro Pulsed Plasma Thruster

Gregory G. Spanjers*, John H. Schilling†, Scott Engelman‡, and Ronald A. Spores§
Air Force Research Laboratory, Propulsion Directorate
Edwards AFB, CA 93524

ABSTRACT

There is an increased requirement for microsatellites to support such future missions as formation-flying space-based radar, space control, and on-orbit satellite servicing. Devices that can provide precise impulse bit in the 10 μN range may be enabling for a new fleet of 25-kg class spacecraft supporting these missions. In response to this need the Air Force Research Laboratory is developing a miniaturized propulsion unit: the Micro Pulsed Plasma Thruster (Micro-PPT). Like a standard PPT, The Micro-PPT uses a surface discharge across the face of a solid Teflon™ propellant to create and accelerate a combination of plasma and neutral vapor. However the Micro-PPT substantially differs from the standard design by using a self-igniting discharge and eliminating the separate igniter and trigger circuit from the thruster. This simplification enables the order-of-magnitude reductions in the thruster size and operational power level required to meet the microsatellite propulsion requirement.

* Leader, AFRL Electric Propulsion Group, Member AIAA
† Research Engineer, SPARTA Inc., Member AIAA
‡ Research Engineer, Raytheon STX
§ Chief, AFRL Spacecraft Propulsion Branch, Member AIAA

I. INTRODUCTION

The Micro-Pulsed Plasma Thruster (Micro-PPT) is a simplified, miniaturized version of the Pulsed Plasma Thruster designed primarily for stationkeeping and primary propulsion on microsatellites. The primary attractive features are the use of a solid inert propellant (Teflon™), expected high-Isp due to the use of electromagnetic acceleration, and a simple, lightweight design based largely on previously flight-qualified electronic components. Prototype PPTs have been fabricated and at least one design has demonstrated long life in laboratory tests. Thus, the Micro-PPT is believed to be a near-term design that could be made available for flight with a modest amount of engineering.

For 100-kg class microsatellites, such as the Air Force TechSat 21 flight to demonstrate space-based radar, the Micro-PPTs can provide propulsive attitude control and a portion of the stationkeeping[1]. For 25-kg class or smaller microsats, suitable for use in a fully deployed space-based radar formation, the Micro-PPTs can provide all stationkeeping and attitude control. The micro-PPTs can also provide primary propulsion to form the space-based radar formation, however the time to create the formation may be unacceptably long.

A. Background

While the Micro-PPT retains some design similarity with the standard PPT, it is fundamentally different in critical areas that enable the required reductions in mass, size and power. For a standard PPT, shown schematically in Fig. 1, a DC-DC converter charges an integrated capacitor from the 28 V spacecraft bus to 1500 V. A second DC-DC converter similarly supplies 600 V to a smaller capacitor in the trigger circuit. The

specific voltages used are from the LES 8/9 PPT [2] flight-qualified in the 1970's, however modern flight units operate in a similar regime[3]. The PPT discharge is initiated by a TTL pulse applied to the semiconductor switch in the trigger circuit. The trigger discharge fires a sparkplug embedded in the cathode, providing enough surface ionization or seed plasma to initiate the main discharge across the Teflon™ propellant face. The solid propellant is converted to vapor and partially ionized by the electric discharge. Acceleration is accomplished by a combination of thermal and electromagnetic forces to create usable thrust. As the propellant is consumed over some 17 million discharges, a negator spring passively feeds the 25-cm-long propellant bar forward between the electrodes.

The Micro-PPT retains the use of a solid propellant from the standard PPT, which is beneficial towards reducing the thruster size, mass and complexity. The primary differences lie in the electronics. The Micro-PPT uses only 1 circuit, and therefore 1 DC-DC converter.

Micro-PPTs have been designed and tested using two classes of designs, triggered and self-breaking. A triggered Micro-PPT uses semiconductor switches to create the pulsed discharge across the Teflon™ propellant. A Self-Breaking Micro-PPT applies the high-voltage charge directly to the propellant face. When the charge voltage exceeds the surface breakdown voltage, the discharge self-ignites. The self-breaking design is simpler and up to 5 times lighter than the triggered design, however additional research to understand the propellant ablation is required to achieve the longer life times attained in the triggered design.

Common to both designs is the propellant module. The Micro-PPT uses a coaxial geometry with inner conductive cathode and an outer conductive shell for the anode. The propellant is an annular rod of Teflon™ between the two concentric cylindrical electrodes. There is no equivalent to the sparkplug igniter used in the standard PPT. In both designs, the Micro-PPT discharge is ignited through an over-voltage at the propellant module tip. The breakdown initiates the surface discharge across the propellant face and the concomitant propellant phase transformation and acceleration.

II. Micro-PPT Designs

A. Triggered Micro-PPT

A photograph of a prototype Triggered Micro-PPT is shown in Fig. 2. Figure 2 shows the propellant module, a pulser box (containing the capacitors, switches, and a transformer), and a transmission connecting the two. The mass of the prototype unit is 500 gm, more than a 10X reduction in mass from the 6 kg of an optimized standard PPT. The prototype was assembled to determine functionality, and has not been optimized to minimize the mass. With dedicated engineering, mass reductions of a factor of two should be realizable.

The Triggered Micro-PPT is shown schematically in Fig. 3. The device uses a circuit similar to the trigger circuit from the standard PPT to induce the surface discharge on the propellant module. A DC-DC converter steps up the 28 V spacecraft bus voltage to charge the integrated capacitor. The required charge voltage is dependent primarily on the dimensions of the propellant module and the characteristics of the optional voltage amplification mechanisms. Other factors such as voltage rise-time, propellant surface

applied to a single propellant module without failure. These discharges were performed over a variety of conditions, however there is no reason not to expect similar functionality in a controlled life test.

Following a large number of discharges, the propellant face can exhibit signs of "gouging," where the bulk of the ablation occurs in a localized region and the remainder of the propellant is relatively pristine. This does not appear to be a concern from a functionality perspective but it is clearly a waste of propellant mass. The cause is presently believed to be insufficient discharge energy to propellant area. The discharge energy cannot be arbitrarily increased to avoid the gouging, since this places an additional burden on the electronics. The electronics can generally be made more robust by adding mass. Optimizing these trade-offs is a subject of current research in the Micro-PPT development.

Pulsed voltage amplification is considered for the Triggered Micro-PPT ~~in order~~ to minimize the requirements (and mass) of the DC-DC converter, and still achieve sufficient voltage at the propellant face to ignite the surface discharge. The amplification can be accomplished using several techniques. A 1:3 transformer is used in the prototype unit solely for convenience, as several such components were available from conventional PPT trigger units in inventory. Different step-up ratios need to be considered ~~in order~~ to optimize the system. Alternatively, a Marx technique can be used whereby a series of capacitors are charged in parallel and then switched to discharge in a series at higher voltage. A Marx bank with N stages will have an output voltage magnified by a factor of N over the charging voltage. More difficult, but still viable, is to use an inductive stacking technique where a single capacitor is discharged into several

The capacitor is directly charged by the DC-DC converter to a voltage sufficient to achieve the surface breakdown at the end of the propellant module. The mass of the DC-DC converter will be higher than that used in the triggered case since the required voltage is higher. The key trade-off is whether this increased mass is offset by the decreased mass and added simplicity achieved through eliminating the switch and pulsed voltage amplification mechanism.

Figure 7 shows the propellant breakdown voltage for the Self-Breaking PPT case measured in the same fashion as was used for the triggered case. Two propellant sizes are shown: 3.58-mm diameter (0.9-mm of cathode, 3.1-mm propellant diameter, 0.24-mm anode wall) and 2.21 mm (0.55-mm cathode, 1.80-mm propellant diameter, 0.21-mm wall). Tests were conducted with 0.088 μF and 0.25 μF capacitors with charge voltages of 8 kV and 5 kV. Charge current was adjusted to maintain a discharge rate generally between 0.5 and 2 Hz. The two cases with 0.25 μF terminated in less than 30 minutes due to an inability to consistently achieve a surface breakdown within the voltage range of the 10 kV supply. The case with an 0.088 μF capacitor functioned for 145 minutes and then also terminated due to an inability to consistently achieve a breakdown within the voltage range of the 5 kV supply. The propellant face in these cases remains relatively clean; however, the face changed from flat to a conical shape. The increases in the required voltage breakdown may be a result of an increase in the path length across the face of the propellant between the electrodes as the conical shape develops. Alternately, electrode erosion during operation may result in a smooth, rounded cathode tip with little field enhancement compared to the freshly-machined cathode surface at the beginning of the test.

In Fig. 8c, the module is fabricated to include a micro-machined spring. This design minimizes electrode erosion and subsequent concerns regarding spacecraft contamination, at the added expense of increased complexity and mass. Fabricating micro-machined springs at the required dimensions is well within current capabilities. The key technical challenge may be avoiding propellant sticking in the long tube as it is being fed forward. No attempts have been made to fabricate or test modules using the spring-fed design.

It is clear from the propellant ablation characteristics in the Triggered Micro-PPT and from the increases in breakdown voltage in the Self-Breaking Micro-PPT that understanding the propellant ablation is critical to optimizing the Micro-PPT designs. To investigate the propellant ablation, a separate test apparatus is used where a series of fixed energy discharges are created across the propellant, triggered by an auxilliary sparkplug, independent of the specific Micro-PPT electronics design. Figure 9 shows the propellant face of a 6.35-mm diameter propellant module (1.70-mm cathode, 5.50-mm propellant diameter, 0.43-mm anode wall) after 40,000 discharges at 5 J fired at 2 Hz. The propellant is clean with no significant conical shape. Instead, the propellant is observed to recess slightly slower near each electrode, possibly due to the heat transport through the copper electrodes acting to cool the Teflon™. The central cathode recedes at nearly the same rate as the propellant, with an approximately 1/8" protrusion past the propellant face in Fig. 9. Further testing on the same propellant module increased the total discharges to 110,000. The propellant obviously receded further into the anode shell, however the cathode protrusion past the propellant face stayed about the same. The propellant ablation rate during these tests was 8.7 μg/discharge at 5 J. This rate,

region blocks particulates from trajectories in the rear-plane of the thruster. Thus, the Micro-PPT may realize additional mass savings by not needing the auxiliary ceramic nozzles that the standard PPT uses to successfully block spacecraft contamination.

III. Discussion

A fundamental issue between the two Micro-PPT designs, other than the clear difference in mass and complexity, may by the dominant failure mode. For the Triggered Micro-PPT, presuming that the capacitors are correctly sized for the proposed mission, the dominant failure is the semiconductor switch (SCR). However, SCRs are commonly used in space applications including, for example, in the trigger circuits of flight-qualified standard PPTs. With correct design and testing, an SCR should be able to survive a Micro-PPT mission life provided the current and voltage limitations imposed by the switch do not unacceptably limit ~~the~~ thruster performance. For the Self-Breaking Micro-PPT the dominant failure mode is increases in the surface breakdown voltage past the charging capability of the DC-DC converter or the voltage rating of the capacitor. In laboratory tests to date, these voltage increases are believed to be primarily due to changing geometry, either of the propellant face or of the central cathode. Based on the differences in the propellant ablation between the two Micro-PPT designs, coupled with the tests on the 6.35 mm propellant module, it is believed that the ablation characteristics can be controlled through a judicious choice of geometry, materials, and discharge energy.

For each of the module designs, and in particular the designs of Fig. 8a and 8b, the propellant modules possess reasonable rigidity, which decreases during the mission

electric propulsion laboratories. If the Micro-PPT propellant consumption scales with energy from the standard 20 J PPTs, the Micro-PPT operating at 1 J will ablate 1.4 μg of propellant. Thus, 7100 discharges are required to achieve a 1% accuracy. However two systematic uncertainties remain. Transient effects, attributed to thermal effects in the propellant[9], have not been characterized at the Micro-PPT level. This effect could raise the required number of discharges by a factor of 2 or more. Second, design constraints in the Micro-PPT make it impossible to simply weigh the propellant. The propellant is rigidly attached to the electrodes; thus, any change in propellant mass necessarily includes electrode mass loss. The small dimensions of the microthruster often require the propellant module to be soldered into the thruster. This makes a propellant mass measurement difficult since a small drop of solder exceeds the total propellant consumption in a typical test run. The lack of measurement capability may soon impede microthruster research and development. It is difficult to assess the effect of changes on performance when the performance cannot be measured with any degree of accuracy at the design power levels.

IV. Summary and Conclusions

Micro Pulsed Plasma Thrusters have been developed and tested in two basic designs. The Triggered Micro-PPT uses a pulse of energy at the face of a coaxial Teflon™ propellant module to create a surface discharge leading to vaporization, ionization and acceleration. The Self-Breaking Micro-PPT applies the high voltage on a slow time scale directly to the propellant face. The transition to a surface discharge is through a surface breakdown due to overvoltage. The Triggered Micro-PPT offers a

thruster mass reduced a factor of 10 from a standard PPT. The Self-Breaking design offers a 60 times mass reduction.

The Triggered Micro-PPT has been observed to exhibit long lifetimes with no fundamental failure modes. The dominant failure is damage to the SCR switch which can be avoided through judicious choice of the circuit energy, voltage, and current. One flaw in the triggered design is a tendency for the propellant to gouge out in a localized region, which is believed to be a result of insufficient energy per propellant face area. This flaw is expected to lead to superfluous propellant mass, not to thruster failure. The Self-Breaking Micro-PPT exhibits a gradual increase in breakdown voltage that is attributed to changes in the propellant or cathode geometry over time. In both designs it is clear that increased research and understanding of the ablation mechanisms and rates, and their dependencies on discharge voltage, energy, and electrode material is crucial to optimizing the Micro-PPT designs.

IV. Acknowledgements

The authors acknowledge the assistance of David White, Sparta Inc., in performing some of the Micro-PPT tests. Portions of the Micro-PPT development are supported by an Air Force Office of Scientific Research contract monitored by Mitat Birkan. The Micro-PPT designs are covered by a provisional patent and have a full patent pending.

References

[1] Schilling, J.H., Spores, R.A., and Spanjers, G.G,“Micropropulsion Options for the TechSat21 Space-Based Radar Flight,” submitted to the Journal of Propulsion and Power Special Issue on Micropropulsion, ~~Jan~~ January 1999.

[2] Vondra, R. J., and Thomassen, K. I., “Flight-Qualified Pulsed Electric Thruster for Satellite Control,” J. of Spacecraft and Rockets, Vol. 11, No. 9, 1974, pp. 613 – 617.

[3] Meckel, N. J., Cassady, R. J., Osborne, R. D., Hoskins, W. A., and Myers, R. M., “Investigations of Pulsed Plasma Thrusters for Spacecraft Attitude Control,” 25th International Electric Propulsion Conference, paper 97-128, Cleveland, Ohio, ~~Aug~~ August 1997.

[4] Spanjers, G.G., Lotspeich, J.A., McFall, K.A., and Spores, R.A., "Propellant Inefficiency Resulting from Particulate Emission in a Pulsed Plasma Thruster," Journal of Propulsion and Power, Vol. 14, No. 3, May-June 1998.

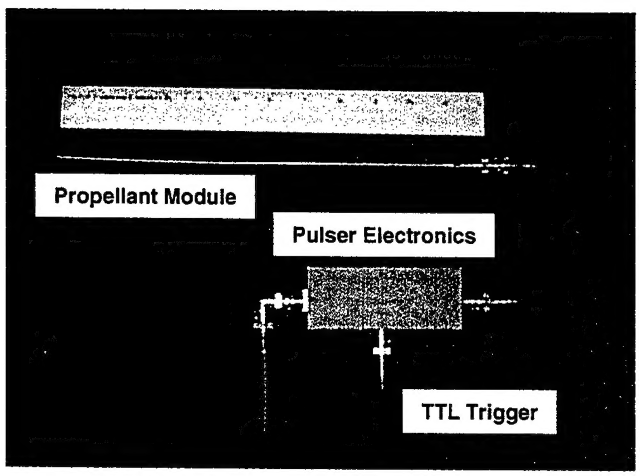
[5] Sciulli, D., “Self-Consuming Satellite” submitted to the Journal of Propulsion and Power Special Issue on Micropropulsion, Jan 1999.

[6] Haag, T. W., “PPT Thrust Stand,” AIAA paper 95-2917, July 1995.

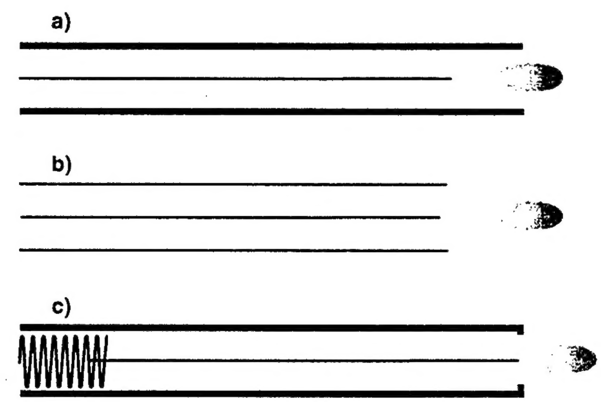
[7] Cubbin, E. A., Ziemer, J. K., Choueiri, E. Y., and Jahn, R. G., “Laser Interferometry for Pulsed Plasma Thruster Performance Measurements,” 24th International Electric Propulsion Conference, IEPC paper 95-195, ~~Sept.~~ September 1995.

[8] Burton, R. L., Wilson, M. J., and Bushman, S. S., “Energy Balance and Efficiency of the Pulsed Plasma Thruster,” AIAA paper 98-3808, July 1998.

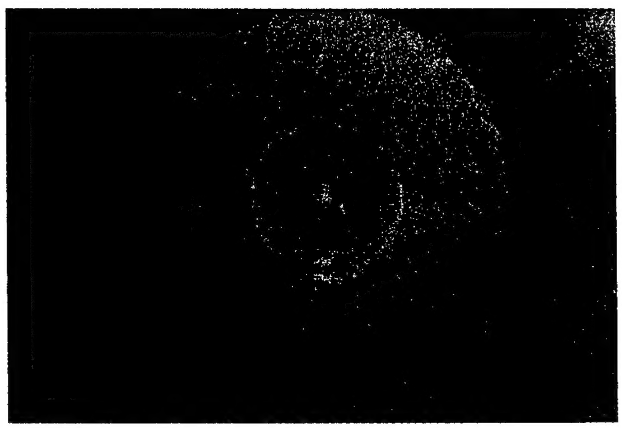
[9] Spanjers, G.G., Malak, J.B., Leiweke, R.J., and Spores, R.A., “The effect of propellant temperature on efficiency in a pulsed plasma thruster,” Journal of Propulsion and Power, Vol. 14, No. 4, July-August 1998.



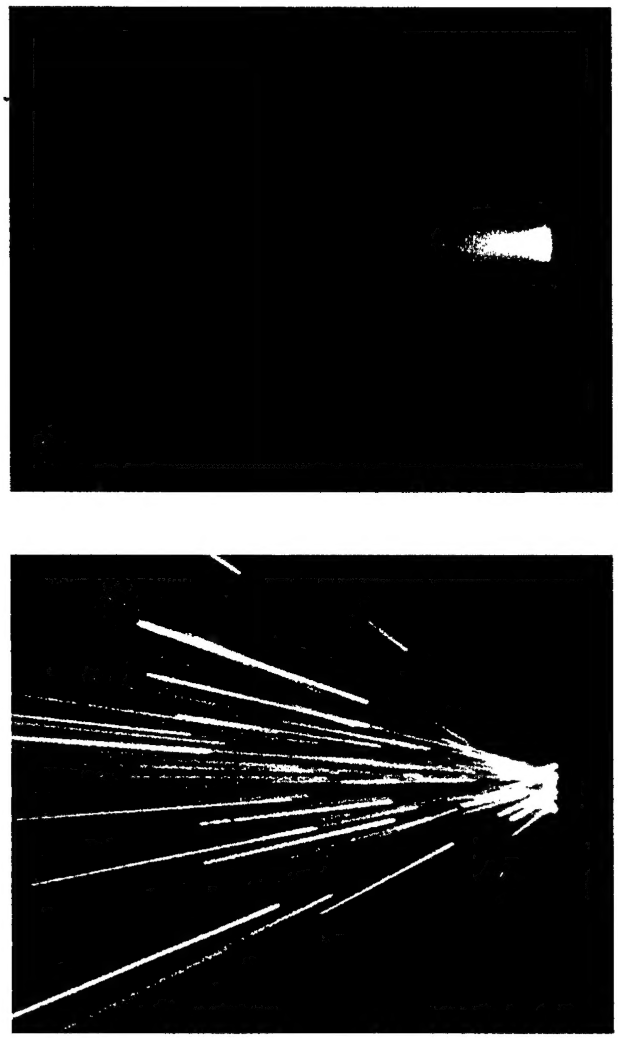
Spanjers at al., JPP, Fig. 2 of 10



Spanjers at al., JPP, Fig. 8 of 10



Spanjers at al., JPP, Fig. 9 of 10



Spanjers at al., JPP, Fig. 10 of 10